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13. ABSTRACT (Maximum 200 words) The research focused upon the creation of engineering materials that mimic some of the attributes of naturally occurring biological materials. This was accomplished by blending different combinations of actuators, sensors, microprocessors and control algorithms in host composite materials. Comprehensive theoretical, experimental and computational investigations were undertaken and the resulting methodologies applied to a diverse group of engineering systems including beams, plates, linkages, and robots.				
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Final Report

U.S. Army Research Office Contract DAAL03-90-G-0052

Smart Composite Structures Featuring Embedded Hybrid Actuation and Sensing Capabilities: An Analytical and Experimental Investigation

Principal Investigators:
M.V. Gandhi and B.S. Thompson

The research prosecuted under this contract focused upon the creation of engineering materials that mimicked some of the sophisticated attributes of naturally-occurring biological materials. Biological materials have evolved throughout the millennia to an optimal state and there is much that *Homo sapiens sapiens* can learn from them in our relentless quest for superior materials for new generations of weapon systems.

Naturally occurring materials are simultaneously designed and manufactured at ambient conditions. At the highest level they feature a blend of attributes analogous to the following engineering terms: actuators, sensors, microprocessors, and control algorithms which are collectively housed in a host structural composite material. The utilization of these primary ingredients in the synthesis of new classes of smart materials with complex macrostructures was the primary objective of this research investigation.

A suite of comprehensive eclectic investigations was undertaken by exploiting theoretical, experimental and computational methodologies and protocols. Hybridization, namely the integration of different technologies and methodologies to ensure optimal performance under variable service conditions by exploiting the most desirable attributes of each, was a thread woven throughout the fabric of this research program. This was motivated by the observation that no single technology or methodology can achieve the desired optimal performance characteristics when subjected to diverse, dynamically changing, operating conditions.

The primary ingredients of the research investigations were various functional materials, such as electro-rheological fluids, shape-memory alloys, piezoelectric ceramics and PVDFs for actuation purposes; continuous fibrous polymeric materials which provide the freedom to create materials with diverse structural characteristics while supporting and housing the actuators and sensors; fiber optic sensing systems and electrical-resistance sensors to monitor the dynamical responses of materials and structures; and hybrid controllers to orchestrate the response of a hierarchy of different controllers and materials. This situation was particularly complicated when fluidic actuators were embedded in materials and structures.

The research program progressed at two levels. A fundamental basic level was employed to develop and refine generic tools for broad applicability in practice. An applied level was employed to transfer these tools to practice through investigations of diverse classes of systems fabricated with these new materials. These investigations included studies of linkage mechanisms, the elastodynamic responses of beams and plates subject to different types of excitations and boundary conditions, and the vibrational responses of robotic arms fabricated in lightweight smart materials. This latter philosophy permitted domains of applicability to be established for the theories.

Much time was invested in understanding and synthesizing electro-rheological fluids for their utility in the synthesis of smart materials. These fluids belong to a class of colloidal suspensions whose global behavior can be changed by the imposition of an electrical field upon the fluid domain. Thus if they are embedded in a structure whose characteristics satisfy specified criteria, the behavior of the structure can be controlled by changing the behavior of

the fluid through the imposition of an electrical excitation.

A new generation of rheometers was developed in conjunction with *Rheometric Inc.* to impose electrical potentials on fluid specimens. This technology transfer initiative permitted a variety of hydrous and anhydrous fluids to be characterized featuring different carrier fluids, particles, surfactants, and particulate concentrations. Subsequently mathematical models were developed for these non-Newtonian fluids, and solutions sought using finite element formulations.

Variational principles were developed for beams fabricated with composite materials and piezoelectric plate actuators that were solved using finite element schemes. Theoretical and experimental studies of slider crank mechanisms with connecting rods fabricated from smart materials were also undertaken. Similar studies of beams fabricated from glass polyester materials with embedded NiTi shape-memory wires were also completed. Health monitoring protocols were the subject of studies of composite beams containing embedded fiber-optic sensors and several types of actuators. Optimal hybrid control strategies were developed in a theoretical and experimental study of flexible robot arms focused upon minimizing the settling time, the rise time and the time of overshoot for high-speed maneuvers. Fuzzy set theory was applied to solve a class of multi-objective optimal design requirements for composite-based robot arms. Finally, a study was completed on design-for-manufacturing strategies for incorporating manufacturing uncertainties in the robust design of composite structures. This investigation was motivated by the observation that the design and manufacture of composite parts are inextricably intertwined because the manufacturing process is not only responsible for the creation of the part but it is also responsible for the creation of the macrostructure too, and hence the material properties.

Many of the ideas and results generated by this research program were published by the Principal Investigators in a book entitled, *Smart Materials and Structures*, published by Chapman and Hall of London. This book was the first to be published on this embryonic scientific field.